VIRTUAL REALITY IN TELEROBOTICS

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Abstract - *Computer graphics or Virtual Reality (VR) techniques developed by the Advanced Teleoperation (ATOP) project at the Jet Propulsion Laboratory (JPL) for the control of remote robot arms are briefly summarized. The techniques are primarily being developed for space applications, but the results are equally applicable to terrestrial telerobotic controls. VR techniques offer very valuable task visualization aids for planning, previewing and predicting robotic actions, operator training, and for visual perception of non-visible events like contact forces in robotic tasks. The utility of computer graphics in telerobotic operation can be significantly enhanced by high-fidelity calibration of virtual reality images to actual TV camera images. This calibration will even permit the creation of artificial (synthetic) views of task scenes for which no TV camera views are available.*

1. INTRODUCTION

The term "teleoperation" (or "telerobotics") denotes a remote control operation where the robot anti operator are physically separated by some distance, and there may exist some communication time delay between the operator and remote robot. A key feature of this operation setting is that the operator's perceptive, cognitive, and manual skills are required to perform the remote operation successfully and efficiently in a control station. The purpose of this paper is to describe and discuss computer graphics techniques that can aid the operator to elevate teleoperation performance to new levels of capabilities.

The role of computer graphics displays in teleoperation includes (i) task visualization for planning teleoperator actions, (ii) motion or action preview prior to actual execution of motion, (iii) predicting motions in real time when there is a communication time delay between operator control station and remote robot, (iv) help operator training before the operator starts exercising the remote hardware, (v) enable visual perception of non-visible events, and, in general, to serve as a flexible operator interface modality to the remote system for implementing control configuration editors anti system Status monitors, replacing complex switch board and analog display hardware; see more on this in [1] and [2].

Task visualization is a key problem in teleoperation since most of the operator's control decisions are based on visual information. The capability of previewing motions enhances the quality of teleoperation by reducing trial-and-error approaches in the hardware control and by increasing the operator's confidence in control decision making during task execution. Predicting consequences of motion commands in real time under communication time delay permits longer action segmentations as opposed to the move-and-wait control strategy usually employed when no predictive display is available, increases operation safety, and reduces total operation time. Operator training through a display system is a convenient tool for initial familiarization of the operator with the teleoperated system without actually turning the hardware system on. Visualization of non-visible events enables a graphical representation of different non-visual sensor data and helps management of system redundancy by providing a suitable geometric picture of a multi-dimensional system state.

Task and control visualization examples are summarized in the second section, using computer graphics as a stand-alone or pure virtual reality system, The third section summarizes the calibration technique by which virtual (graphics) and actual (TV) images can be fused into a realistic single perceptive' frame on a monitor screen. Issues on the visualization of non-visible things and the training of operators using VR techniques, are treated in sections four and five.

2. TASK VISUALIZATION

The computer graphics system for task and control visualization in the ATOP control room was developed for a dual-arm workcell surrounded by a gantry robot frame providing mobility for a stereo and two mono TV cameras, each on a pan-tilt base, in three orthogonal planes. Camera focus, zoom, and iris can also be remote controlled. The workcell housed two eight-d.o.f. AAI arms, each equipped with a "smart" robot claw-hand which can sense both the grasp force at the base of the claws anti the three orthogonal forces/moments at the base of the hand. The task environment in the workcell simulated the Solar Maximum Satellite Repair (SMSR) which was actually performed by two astronauts in space suits in the Space Shuttle cargo bay in 1983. (Note that this satellite was not designed for repair!) The goal of the experiments in the ATOP workcell was to show how to do the same repair in a teleoperation mode. To achieve this goal, the use of computer graphics offered an indispensable help in many ways.

Figure 1 illustrates a teleoperated SMSR workcell layout visualization in a top view to determine the mounting of the dual-arm system relative to the satellite mock up, with reach envelopes of the robots overlaid on the workcell display, for various repair subtasks. Figure 2 illustrates the evaluation of viewing conditions together with the evaluation of alternative use of the dual-arm system's redundant capabilities for an electrical connector unbolting subtask. Altogether, twelve major sequential subtasks are implied in the Main Electrical Box (MEB) change-out in the SMSR mission, and each subtask requires the use of some tool (screwdriver, scissors, etc.) This corresponds to a large set of task and control visualization off-line analysis by computer graphics, also taking account of workspace, arm kinematics, use of tools, " and viewing constraints. It is noted that the motion of the robot arms' graphics images during task and control simulation are controlled by the same inverse/forward kinematics control software that controls the actual hardware system.

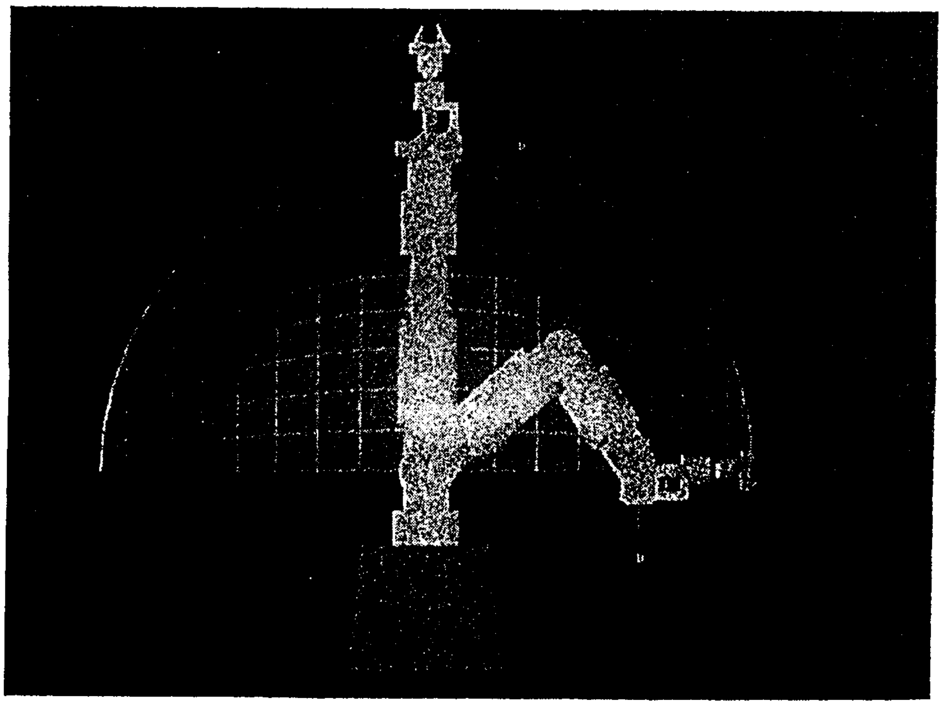


Figure 1. Visualization of Workcell Layout with Reach Envelope Overlays

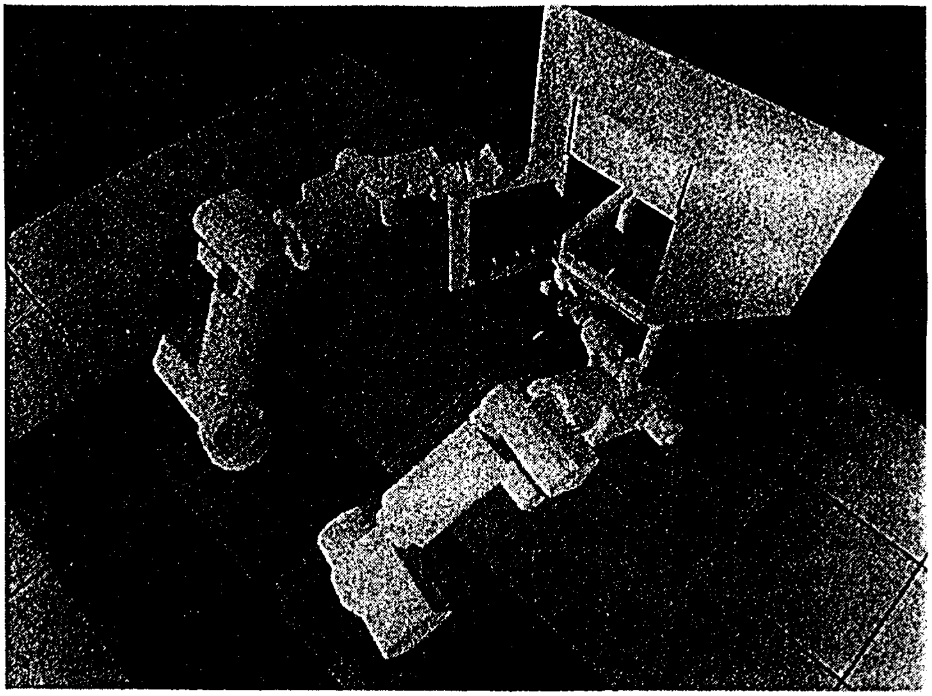


Figure 2. Visual Evaluation of Redundancy Management and Viewing Conditions

Two major conclusions resulted from the SMSR graphics task and control visualization off-line analysis: (i) The full task can only be performed with the given dual-arm setting if the base of either the dual-arm system or the task board (prefer-ably the task board) is movable in two directions in a plane by about ± 45cm in each direction and rotatable by about ± 20 degrees, (ii) a small TV camera mounted to the base of the right arm's end effecter would considerably contribute to the effectiveness and safety of several subtask performances.

Figure 3 illustrates a graphics operator interface to the control of the dual-arm telerobot system for SMSR experiments, as a result of the off-line graphics task and control simulation analysis. The subtasks are listed in the lower right insert, four preview control options are listed in the upper left insert, anti the upper right insert lists some current status messages. It is noted that the graphics image of the two arms is updated in real time at a rate of at least 15Hz so that the operator can always view the full system configuration even when all TV cameras are focused and zoomed on some particular subtask details. More on the SMSR task and control graphics visualization and the resulting graphics operator interface work can be found in [3].

3. FUSED GRAPHICS AND TV IMAGES

The actual utility of computer graphics in teleoperation to a high degree depends on the fidelity by which the graphic models represent the teleoperator system, the task, and task environment, The JPL advanced teleoperation effort in the past few years was focused on the development of high-fidelity calibration of graphics displays. This development has four major ingredients. First, creation of high-fidelity 3-D graphics models of remotely operated robot arms and of objects of interest for robot arm tasks. Second, high-fidelity calibration of the 3-D graphics models relative to given TV camera 2-D image frames which cover the sight of both the robot arm and the objects of interest. Third, high-fidelity overlaying of the calibrated graphics models over the actual robot arm and object images in a given TV camera image frame on a monitor screen as seen by the operator. Fourth, high-fidelity motion control of robot arm graphics image by using the same control software that drives the real robot, see [4] and [5].

These high fidelity fused virtual and actual reality displays became very useful tools for planning,

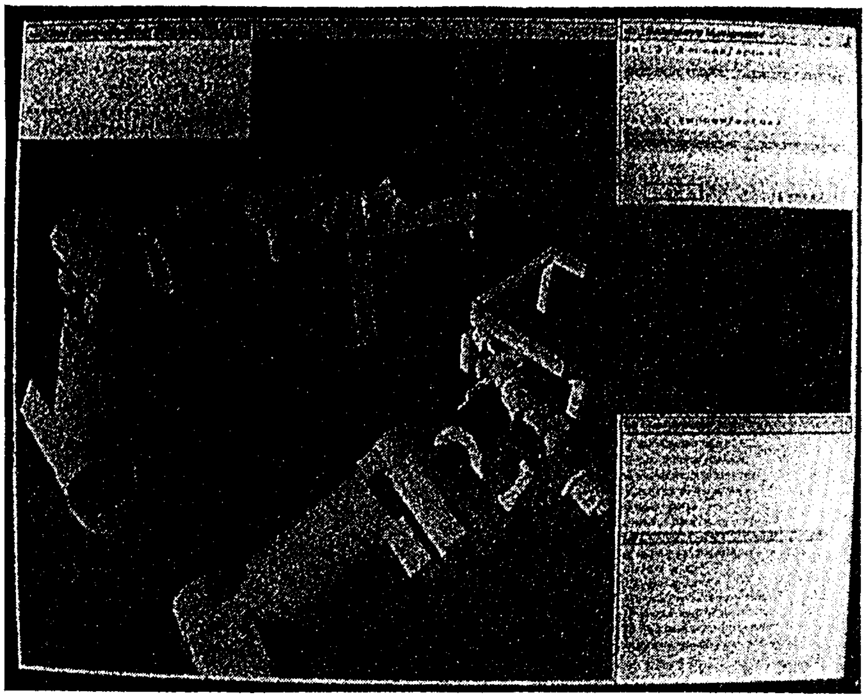


Figure 3, Graphics Operator Interface for Preview and On-Line Visualization, with Task Script Titles and Redundancy Mgmt. Status

predicting, and previewing robotic" actions, without commanding and moving the actual robot hardware. The operator can generate visual effects of robotic motion" by commanding the motion of the graphics image of the robot superimposed over TV pictures of the live scene. Thus, the operator can see the consequences of motion commands in real time, before sending the commands to the remotely located robot. This calibrated virtual reality display svstem can also provide high -fidelity synthetic or artificial TV camera views to the operator. These synthetic views make critical robot motion events visible that otherwise are hidden from the operator in a giver-r TV camera view or for which no TV camera view is available.

3.1 Camera Calibration And Object Localization

Fusion of graphics and actual TV images can be generated by overlaying graphics images over actual TV images, A high-fidelity over-lay requires a high fidelity TV camera calibration and object localization. For this purpose, a reliable operator-interactive camera calibration and object localization" technique has been developed. The current calibration uses a point-to-point mapping procedure, and the computation of the camera calibration parameters is based on the ideal pinhole model of image formation by the camera.

First, the camera calibration is performed by using the manipulator itself as a calibration fixture. The operator enters the correspondence information between 3-D graphics model points and 2-D camera image points of the manipulator to the computer. This is performed by repeatedly clicking with a mouse a graphics model point and its corresponding TV image point for each corresponding pair on a monitor screen which shows both the graphics model anti the actual TV camera images. To improve calibration accuracy, several poses of the manipulator within the same TV camera view can be used to enter corresponding model and TV image points to the computer. Then the computer computes the camera calibration parameters. Because Of the ideal pinhole model assumption, the computed output is a single linear 4x3 calibration matrix for a linear perspective projection.

Object localization is performed after camera calibration, entering corresponding object model and TV image points to the computer for different desired TV camera views. Again, the output is a single linear 4x3 calibration matrix for a linear perspective projection.

The actual camera calibration and object localization computations are carried out by a combination of linear and nonlinear least-squares algorithms, and

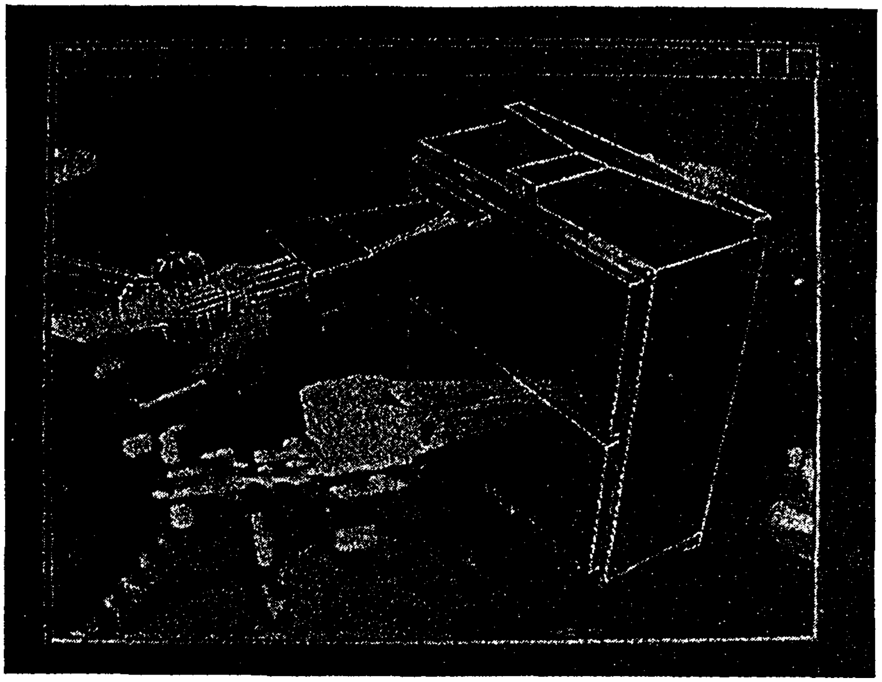


Figure 4. A Predictive/Preview' Display of End Point Motion

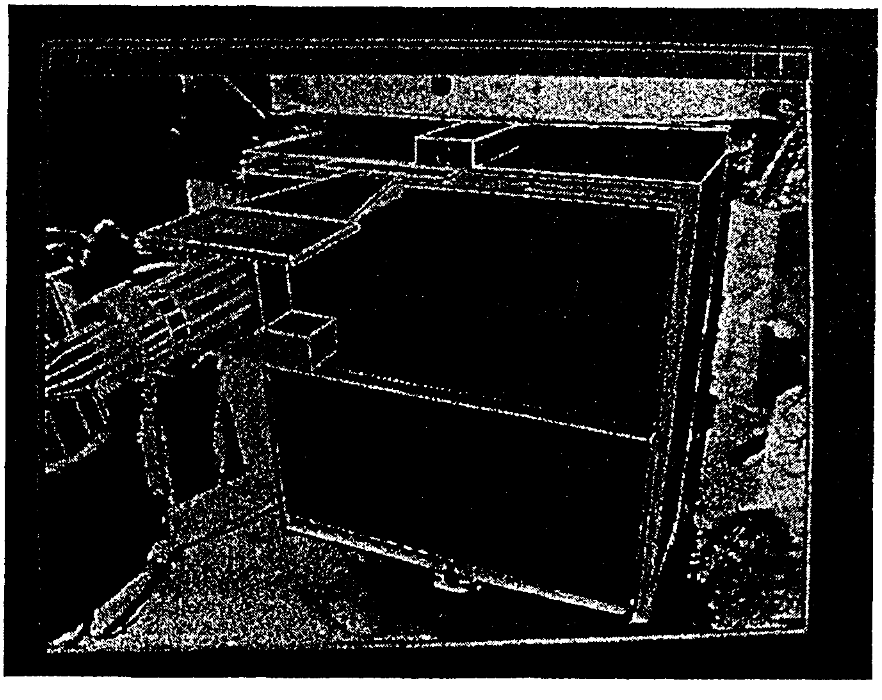


Figure 5. Status of Predicted End Point after Motion Execution, from a Different Camera View, for the Same Motion Shown in Figure 4

and collision detection. TELEGRIP CLI (ascii-text Command Line Interpreter) commands include INQUIRE COLLISIONS (reporting collision and near miss status) and INQUIRE MINIMUM DISTANCE (reporting minimum distance between parts or devices). TELEGRIP GSL (Graphics Simulation Language) also supports ray cast () function that computes the intersection distance from a point in a specified (ray cast) direction. Using these object distance computation functions, various proximity sensors can easily be simulated. More on this in [7].

Force/torque sensor can also be simulated by computing virtual contact forces and torques for given simulated geometric contact models. In general, an accurate simulation of virtual contact forces anti torques can be very computation-intensive, but an approximate simulation, for example, a simplified peg-in-hole task, can be accomplished without difficulty, as illustrated in Fig 6 and described in detail in [5]. In this graphics simulation, the hole and its support structure are assumed to be rigid with infinite stiffness, while the robot hand holding the peg is compliant for all three Cartesian transitional axes anti also for all Cartesian rotational axes. (It is further assumed that the compliance center is located at a distance L from the tip of the peg with three lateral springs k_X, k_y, and k_Z and three angular springs k_{mx}, k_{my}, k_{mz}. Both the operator-commanded anti the actual positions of the peg are described by the position of the compliance center. For a given operator-commanded peg position, the actual peg position after compliant accommodation" can be different, depending upon the current state of the peg of whether the peg is currently in the hole or not. For the peg-not-in-hole state, two conditions" are considered: no-touch or peg-on-wall For the peg-in-hole state, four conditions art' considered: no-touch, peg-side one-point contact, peg-tip one-point contact, or two-point contact.

Figure 7 shows a force-reflecting virtual reality training display for a peg-in-hole task. Contact forces and torques are computed and reflected back to a force-reflecting hand controller in real time. They are also displayed on the upper left corner of the display screen.

4.2 Complex Constrained Workspace

A technique has been recently developed and described in [8] for determining and visualizing the geometric motion capabilities of dual-arm robotic systems when the arms work on an object in a closed kinematic chain configuration, taking account of robot arms' base placement, object dimensions, object holding and contact constraints, and space occupancy conflicts of the two arms' links. This constrained and object orientation restricted motion space is general can be visualized as a complex 3D object with hidden unreachable holes or cavities of varying shapes. The developed technique is an inverse computer vision procedure in the sense that it creates rather than recognizes visual forms.

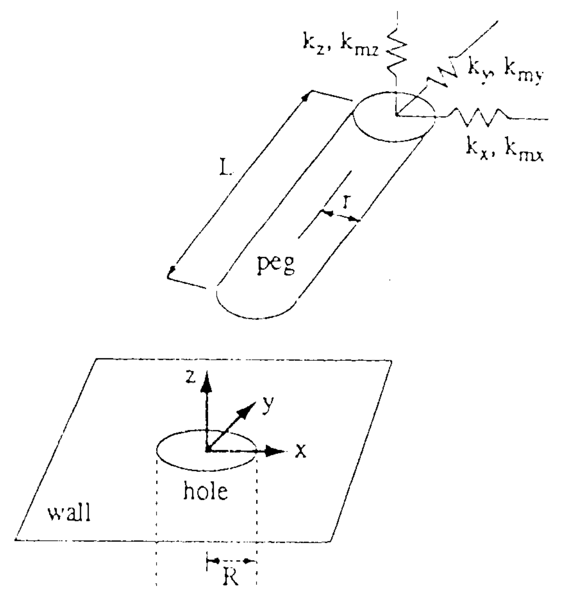
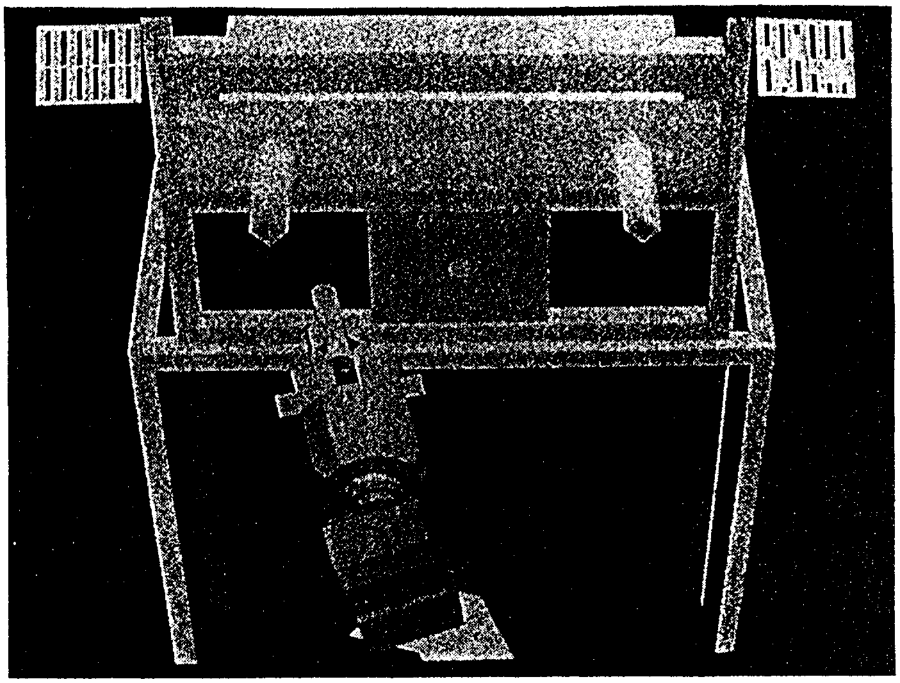
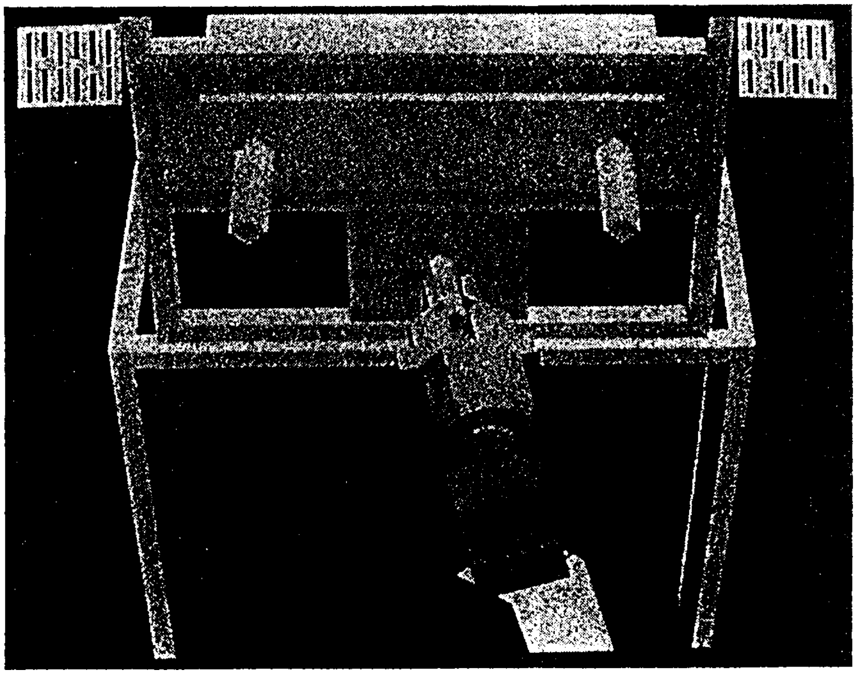


Figure 6. Geometry of a Simulated Peg-in-Hole Task with Lateral and Angular Springs at the Compliance Center

The feasibility of the quoted Visualization technique has been demonstrated through generating 3D semi-transparent motion space images for a dual-arm example shown in Figure 8. in this example, the two robot arms are rigidly connected to a long rod. The motion space considered for this dual-arm case is composed of all positions that the rod center can achieve when the two arms, operating as a rigidly closed chain, hold and move the rod in a fixed orientation. Figure 9 shows a 3D transparent view solution of this problem. This 3D semi-transparent display is a perspective view such that the x-axis is to the left, the)~-axis is to the right, anti the z-axis is to the top. Two thick, black patches, seen to the left and right across the center are the unreachable spaces hidden in the outer light gray reachable space. The bigger transparent light gray object is the reachable space, and the lighter gray empty space



(a)



(b)

Figure 7. A Force-Reflecting Teleoperation Training Display for a Peg-In-Hole Task; (a) before contact, (b) after contact with the wall

parallel to the y-axis passing through the center corresponds to the forced unreachable space that avoids collision with robot bases.

Note that motion space visualization through 3D semi-transparent images will help the operator see the reachable and unreachable regions of the motion space simultaneously. Note also that this inverse computer vision technique can form a solid foundation for an automated task-level geometric path generator for constrained dual-arm motion problems.

5. VR FOR OPERATOR TRAINING

The practical purpose of training is, in essence, to help the operator develop of a mental model of the telerobot system and of the task. During task execution, the operator acts through the aid of this mental model. Some initial operator training can always be performed in a VR setting, without turning on any telerobot hardware. In this setting, the operator' can learn the activity protocol or task script. In fact, the task script itself can represented to the operator in an appropriate VR format.

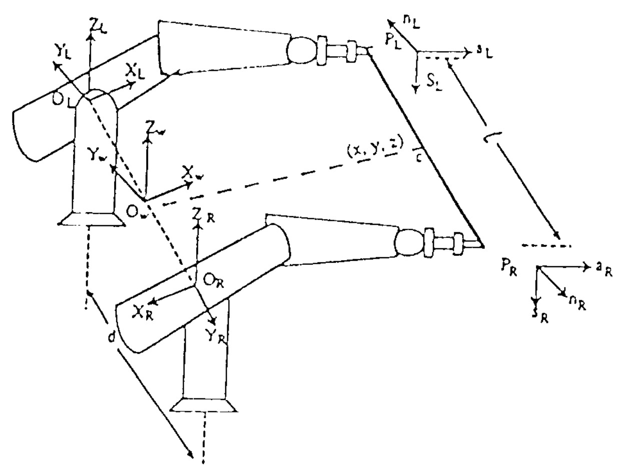


Figure 8. A Long Rod Handled by Two Robot Arms

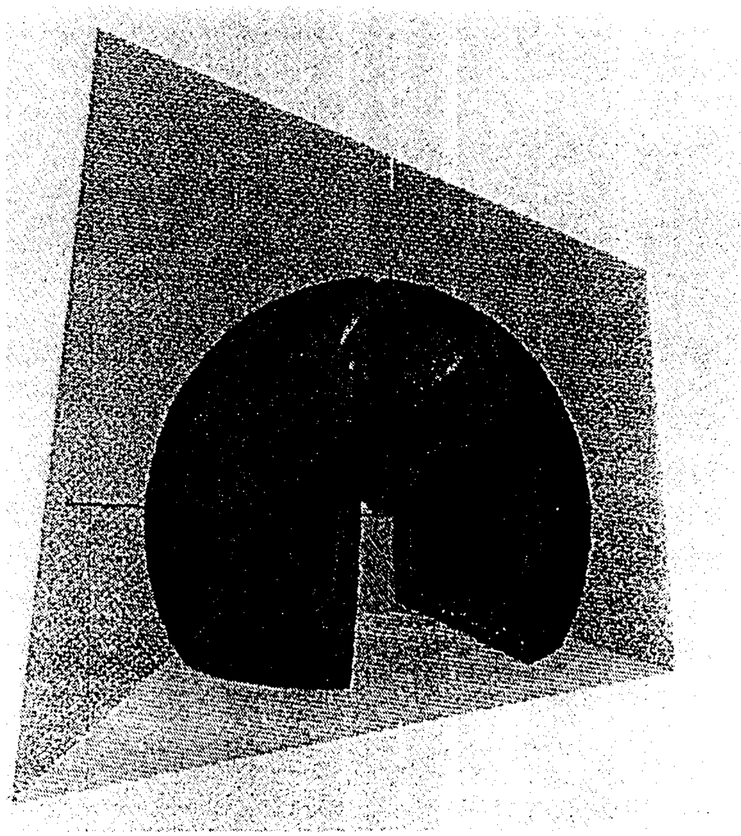


Figure 9. View of the Workspace from X-Y Direction for a Rod of Length 0.5m

The procedure of operator training and the expected behavior of a skilled operator following an activity protocol also offers the possibility of providing the operator with performance feedback messages on the operator" interface graphics, derived from a stored model of the task execution A key element for such an advanced performance feedback tool to the operator is a program that can follow the evolution of a teleoperated task by segmenting the sensory data stream into appropriate phases.

A task segmentation program of this type has been implemented by means of a neural network architecture, described in [9]. It is able to identify the segments of a peg-in-hole task. With this architecture, the temporal sequence of sensory data generated by the wrist sensor on the manipulators are turned into spatial patterns and a window of sensor observations which is related to the current task phase. A partially recurrent network algorithm was employed in the computation. Partially recurrent networks represent well the temporal evolution of a task, as they include in the input layer a set of nodes connected to the output units to create a context memory. These units represent the task phase already executed-the previous state. Several experiments of the peg-in-hole task have been carried out and the results have been encouraging, with a percentage of correct segmentations approximately equal to 65%. More on these experiments can be found in [9] and [1(1].

6. CONCLUSION

A major conclusion is that the application of VR techniques and tools in the design and operation of telerobotic systems enables the performance of more tasks, safer, faster, and inherently cheaper.

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Note: The above references contain more details about hardware and software implementation environment and about quantified experimental results.